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Petrographic Examination of Aggregate and Concrete in Ontario

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PETROGRAPHIC EXAMINATION OF AGGREGATE AND CONCRETE IN ONTARIO

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Abstract: Petrographic examination of aggregate and hardened concrete has been conducted by the Ministry of Transportation since the late 1940's. There were problems in communicating results of petrographic examination of aggregates to engineers. This resulted in the development of the "Petrographic Number" (P.N.) as a way of expressing the quality of coarse aggregate. Four quality categories are recognized: good aggregate (factor 1), fair (factor 3), poor (factor 6), and deleterious (factor 10). The Petrographic Number is calculated by multiplying the percentages of each rock type by the appropriate factor. The products are then added up to arrive at the P.N. Petrographic examination is conducted on sand using automated equipment. The percentage of deleterious (mica, shale) or alkali-reactive components (chert, glass) is reported. Petrographic examination of concrete is also conducted.

Résumé: Le ministère des Transports effectue des examens pétrographiques des agrégats et du béton durci depuis la fin des années 1940. Certains problèmes de communication aux ingénieurs des résultats des examens pétrographiques des agrégats ont été recontrés. C'est pour cette cette raison qu'un "numero pétrographique" (P.N.) a été mis au point, dans le but d'exprimer la qualité des agrégats grossiers. Quatre catégories de qualité ont été établies: bon agrégat (facteur 1), moyen (facteur 3), mauvais (facteur 6), et déiétère (facteur 10). Le numéro pétrographique est obtenu en multipliant les pourcentages de chaque type de roche par le facteur voulu. Les produits sont alors additionnés pour donner le P.N. Les examens pétrographiques sont réalisés sur du sable à l'aide d'équipment automatique. Le pourcentage de composants délétères (mica, schiste argileux) ou alcaliréactifs (chert, verre) est indiqué. Des examens pétrographiques sont aussi réalisés sur le béton.

Keywords: Aggregates, performance, petrographic examination, concrete, classification.

Notes: Appendix I contains examples of old petrographic forms from 1951 to 1976.

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ABSTRACT: Petrographic examination of aggregate and hardened concrete has been conducted by the Ministry of Transportation since the late 1940's. There were problems in communicating results of petrographic examination of aggregates to engineers. This resulted in the development of the "Petrographic Number" (P.N.) as a way of expressing the quality of coarse aggregate. Four quality categories are recognized: good aggregate (factor 1), fair (factor 3), poor (factor 6), and deleterious (factor 10). The Petrographic Number is calculated by multiplying the percentages of each rock type by the appropriate factor. The products are then added up to arrive at the P.N. The higher the P.N., the poorer the quality of the aggregate. A perfect aggregate would have a P.N. of 100. Petrographic examination is conducted on sand using automated equipment. The per cent of deleterious (mica, shale) or alkali-reactive components (chert, glass) is reported. Petrographic examination of concrete is also conducted. Over the years, many problems have been investigated, such as: fire-damaged concrete, frozen concrete, concrete damaged by alkali-aggregate reactions of various types, damage by freezing and thawing, causes of low strength and retarded concrete. In addition, petrographic examination has been used to detect additions of non-standard components to Portland cement.

KEYWORDS: aggregates, performance, petrographic examination, concrete, classification.

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PETROGRAPHIC EXAMINATION OF AGGREGATE

Petrographic examination of aggregates has been done for many years in Ontario. In the specifications for Ontario concrete bridges in 1905 [1] there were the following requirements:

> "... stone used shall be granite, quartzite, fine grained limestone, or other equally strong and durable stone, care being taken to exclude soft limestone, friable sandstone, and stone affected by the atmosphere".

In 1907 A.W. Campbell [2] in his report on Road Improvement in the Province of Ontario made the following statement:

> "A practical man can judge of the qualities of a stone by applying simple tests: by breaking the stone with a hammer, wearing it on a grindstone, crushing it in a blacksmith's vice, scratching with an iron nail, breaking small pieces with the fingers: by such simple means a general idea of the stone can readily be formed, but no test is so conclusive as actual wear on the road".

It would be hard to improve on this advice today. At the beginning of the century the basic doctrine of petrographic examination was known. Certain rock types were more suitable than others. The quality of aggregate could be judged by simple index tests. Field performance or observation of existing roads and structures was the most useful means of determining aggregate suitability. Campbell was, however, only stating existing knowledge of judging the suitability of building materials which must have been practised since the first buildings were erected. Since then, our techniques may have improved but the philosophy has not changed.

The Petrographic Number System

In 1948, Bob Bayne and C.W. Greenland, geologists working for the Ontario Department of Highways, conducted surveys of the condition of concrete pavements in southwestern Ontario [3]. This is a flat lying agricultural area with numerous concrete pavements constructed in the 1920's and 1930's. The climate is severe with many cycles of freezing and thawing each season. The pavements they examined were from 6 to 26 years old with an average age of about 18 years. They rated the suitability of the aggregates on their observation of such defects as popouts, surface scaling, map cracking and general disintegration. Problems due to base failure, settlement or finishing defects were discounted. Of the 50 aggregates, 13 were classed as unsatisfactory, 16 were questionable or borderline and 21 were considered satisfactory.

They were able to collect and test samples of aggregate from the original sources. A summary of their results is shown in Table 1. In

addition to routine durability tests, they also conducted a petrographic examination using as a basis, the procedure of Mielenz [4]. They identified excellent, good, fair and poor varieties of rock. Fair rocks included: moderately weathered limestone and dolostone, fresh coarse grained acid and basic igneous rocks, sandstone, porous limestone and shaley limestone and dolostone. Poor rocks included most cherts (excluding blue/grey unleached chert), shale, badly weathered shaley limestone and dolostone, porous limestone, schist and some gneisses, sandy ferruginous limestone, siliceous limestone, clay, ochre, gypsum etc. This classification was based on their observed performance of these rock types in the concrete pavements and not on a preconceived notion of likely quality.

From the results shown in Table 1, Bayne and Greenland drew the following conclusions: Aggregate performance was not measured by Los Angeles abrasion loss; stone absorption and sulphate soundness loss were slightly related to performance. The most useful correlation of actual performance was with petrographic composition. They recognized, however, the impossibility of deriving useful criteria based on limits for the maximum amount of fair and poor material without rejecting aggregates that performed satisfactorily.

In 1950, Bayne and Greenland experimented with a numerical weighting system. Excellent rock types were given a factor of 0.9. Good rock types were given a factor of 1 to 1.3. Fair rock types had a factor between 1.4 and 3.5 and the poor rocks had factors between 3.5 and 6.0 (Figure 1). The mass per cent of each rock type in a sample was multiplied by the appropriate factor to give a weighted value. The sum of the weighted values was called a Petrographic Number or P.N.. For instance a sample composed entirely of strong, unweathered basalt would have a P.N. of 90 (100% x 0.9). A sample composed entirely of clay or soft shale (factor 6) would have a P.N. of 600. This system had the advantage that it expressed the relative amounts of good, fair and poor material as a single number. This was an excellent tool for comparing the quality of aggregates provided the examination was done in a consistent manner by experienced people.

By 1953, maximum Petrographic Numbers had been arrived at for various uses (Table 2), and the Petrographic Number system was formally adopted for all Provincial highway contracts. Over the first few years there were frequent changes and additions to the classification of rock types to reflect actual field performance and rock types that had not previously been encountered. In 1955, Bayne and Brownridge [5] reported that petrographic analysis was the most significant and useful of all quality tests. They considered it especially useful for noting changes in quality of existing aggregate sources which had been thoroughly investigated using other tests. The procedure was also useful because of the speed with which an experienced observer could judge quality, and its ease of use in the field, often far removed from a laboratory. The 1950's were a time of tremendous development of the Ontario highway system. In remote parts of northern Ontario there was

TABLE 1 -- Relationship between Field Performance and Aggregate Properties, from [3].

	FIELD PERFORMANCE RATING		
	Satisfactory	Questionable	Unsatisfactory
Number of Samples	21	16	13
Magnesium Sulphate per cent loss, ASTM C 88-48T			
Stone	3 (0-6)	6 (1-14)	10 (4-34)
Sand	9 (5-18)	11(7-21)	11 (8-15)
Absorption Per cent ASTM C 127-42			
Stone	1.3 (0.8-2.2)	1.4 (0.7-2.4)	2.2 (1.0-3.0)
Sand	1.5 (0.6-3.0)	1.7 (0.4-3.3)	1.9 (1.2-3.0)
Los Angeles Abrasion, per cent loss, "A" grading ASTM C 131-46	28 (20-38)	27 (19-58)	30 (23-39)
Petrographic Examination per cent by mass			
Good	82 (43-100)	71 (43-94)	66 (8-96)
Fair	15 (0-53)	15 (0-75)	26 (0-70)
Poor	3 (0-10)	14 (0-45)	9 (1-35)

NOTE: 3 (0-6) represents mean and range respectively.

TABLE 2 -- Maximum Petrographic Numbers for Different Types of Construction.

Type of Construction	Maximum Petrographic No.	
	1953	1989
Premium asphalt surface course (H.L.1)	100	120
Asphalt binder and surface course (H.L.4)	160	160*
Asphalt binder course (H.L.8)	160	160*
Concrete Pavements	140	125
Concrete Structures	140	140
Concrete Culverts	155	-
Surface treatment chips	175	160
Granular Base	-	200
Granular Subbase	-	250

*In some areas, the maximum P.N. may be 180 by special provision.

ANALYST D. HANNA DATE 14-7-54 CONTRACT NO. 54-113

PIT NAME DEPT. OF HWYS. SAMPLE NO. 54-14950

ROCK TYPES	DESCRIPTION	Weight in grams.	%	FACTOR	Weighted Value
SEDIMENTS					
Limestone -	Angular - Hard	320	32.0	1.0	32.0
	- Pebble - Sound	200	20.0	1.0	20.0
	- Soft - Slightly weathered	16	1.6	1.5	2.4
	- Rusted			1.4	
	- Mottled			2.0	
	- Mottled with Limonitic stain	5	0.5	3.0	1.5
	- Sandy			2.5	
	- Shaley	15	1.5	4.0	6.0
	- Clayey			4.0	
	- Ochre producing			4.0	
	- Soft - Pitted			2.0	
Dolomite	- Angular - Hard			1.0	
	- Pebble - Sound	30	3.0	1.0	3.0
	- Pitted - Hard or Arenaceous			1.3	
	- Pitted - Soft - Porous			2.0	
	- Soft - Slightly weathered			1.5	
	- Clayey			4.0	
	- Soft Buff			1.4	
Shale	- Limey			5.0	
	- Black - Soft	15	1.5	5.5	8.25
	- Black - Carbonaceous			5.5	
	- Slate			3.0	
Sandstone	- Hard	27	2.7	1.5	4.05
	- Average - Scratches easily			3.0	
	- Soft Friable			4.5	
Chert	- Chert	30	3.0	5.0	15.0
	- Cherty Limestone or Dolomite			4.0	
Clay	- As a product of Limestone or Dolomite			6.0	
	- Clay	12	1.2	6.0	7.2
METAMORPHICS					
	- Siliceous sheared volcanic-med hard			1.3	
	- Siliceous sheared volcanic - soft			2.0	
	- Greywacke - Arkose, etc.	119	11.9	1.0	11.9
	- Granite Gneiss	37	3.7	1.2	4.4
	- Hard Hornblende/Biotite Gneiss	10	1.0	1.4	1.4
	- Quartzite - very fine grained			1.6	
	- Quartzite - coarse grained	7	0.7	1.2	0.8
	- Crystalline Limestone - Hard			1.5	
	- " " " - Slightly Weathered			2.0	
	- " " " - Soft			3.0	
	- Hornblende/Biotite Gneiss Soft	27	2.7	4.0	10.8
	- Soft Schists			4.0	
	- Gniess - Badly Decomposed	51	5.1	5.0	25.5
IGNEOUS					
	- Granites - Syenites - Diorites	17	1.7	1.0	1.7
	- Trap - Andesite - Basalt - Diabase	32	3.2	0.9	2.9
	- Volcanics - Hard	30	3.0	0.9	2.7
	- Volcanics - Medium hard			1.2	
	- Volcanics - Slightly weathered			1.5	
	- Volcanic Ash - very porous			2.0	
	- Volcanics - Decomposed lavas/breccias			4.0	
MISCELLANEOUS					
	- Encrustations			2.0	
	- Cementations			3.0	
	TOTAL	1000	100		161.5

ROCK TYPES	Quality --- Per Cent			
	Excellent	Good	Fair	Poor
SEDIMENTS		55	4.8	7.2
METAMORPHICS		16.3	1.0	7.8
IGNEOUS	6.2	1.7		
TOTAL	6.2	73.0	5.8	15.0

Remarks EXCELLENT = 0.9; GOOD = 1.0-1.3; FAIR = 1.4-3.5; POOR = 3.5-6.0

PETROGRAPHIC NUMBER = 162

FIGURE 1 — Petrographic examination form used in 1954

often no time or means for formal testing of aggregate sources before construction began.

In the 1930's and 40's the bridges built in remote areas had normally been constructed with the materials at hand with no real thought apparently being given to their quality. By the 1960's those structures and highways built with excessive amounts of poor and deleterious rock types were in poor condition and needed replacing. In contrast, those structures built after the implementation of the petrographic number system seldom show damage that can be related to the physical quality of the aggregates.

A critical feature of the petrographic procedure has been the insistence that all changes in classification of the factor applied to the various rock types should only be done after thorough field investigation. These investigations have been a full time occupation for the petrographer. As far as possible, classification is based on observed performance in highways or structures. In some cases, field performance has been limited or entirely lacking. In northern Ontario, construction in remote, undeveloped areas has resulted in investigations of unusual rock types such as carbonatite rich gravels. In these cases, where field performance is lacking, the rocks are classified into quality types based on such properties as strength, porosity, type of fracture, density and toughness. These quality types are then tested in various durability tests such as sulfate soundness, impact, freeze-thaw, absorption and so on, to confirm the petrographic factor applied to each quality type. After some time it is usual to inspect pavements and structures built with these unusual aggregate types to confirm that field performance is satisfactory. In one notable case this was not done. An investigation in 1960, classified all rocks of a late Proterozoic sedimentary formation in the poor category with the result that gravels in the area were seldom used for construction. In 1978, a more extensive investigation was conducted and field performance used in the classification. It was found that many of the rock types previously considered poor, actually had fair to good performance. The original error had been made because of the reliance on laboratory tests which showed excessive disintegration with many 'fair' and 'good' categories. Fortunately, this problem occurred in an area with little impact on supply of aggregate due to inappropriate classification. The lesson that classification should as far as possible be based on field performance and not on pre-conceived notions of likely performance is important if petrographic examination is to be useful. A report by Magni [14] is a good example of the nature of the work necessary to correlate P.N. with field performance of unusual aggregate types.

Development After 1955

The petrographic number system has, over the years, aroused considerable controversy, especially with aggregate suppliers and contractors who felt uncomfortable with a quasi-quantitative system

susceptible to personal bias. In 1958, R.C. Mielenz was consulted to make recommendations to improve the procedure and also to advise on a dispute with aggregate suppliers with chert rich quarries. Mielenz reported [6] that the chert rich and shaley horizons found in these quarries were unsatisfactory for highway use. He recommended changes to the procedures such as: increasing the number of particles examined, the use of stereoscopic microscopes and increasing the number of sieve fractions examined. He also recommended that a petrographer should be available to assist with separation of complex aggregates and to estimate the potential for chemical reactivity. He recommended that a petrographer should be available to assist with separation of complex aggregates and to estimate the potential for chemical reactivity. He recommended that the Petrographic Number system should only apply to physical quality of aggregate and that the report for each sample should list the proportion of specific unsound rock types. His recommendations were followed.

In 1960 the system was considerably simplified. The excellent category was abandoned (factor 0.9). A deleterious category was recognized (factor 10) which included such types as decomposed igneous rocks, clay, shale and ochre. The fractional factor values were abandoned (1.1, 1.2, 1.3, became 1). Good aggregate had the factor 1, fair 3, poor 6 and deleterious 10. These changes made the procedure a little less subjective. The changes adopted in 1960 are still being used in 1989 with little substantial modification (Figure 2).

An important innovation in 1963 was the adoption of different factors for different exposure conditions. For instance, it was recognized that many poor aggregates such as leached or tripolitic chert, while undesirable in concrete were perfectly suitable in granular base and given the factor 1 for that use. Similarly, some aggregates such as slightly shaley carbonate, considered of fair quality in asphalt were considered good in granular base. In 1963, four different environments were recognized with slightly different factors for each. In the 1970's this was simplified to two environments: aggregate confined in asphalt or concrete and unconfined uses in granular base.

Current Procedure

A sample of aggregate is screened on the 19, 13.2, 9.5, 6.7 and 4.75 mm sieves. Samples are prepared of each sieve fraction starting with the coarsest fraction present (that makes up more than 5 per cent of the sample) so that at least 70 per cent of the material is examined. About 200 particles of each fraction are examined. The rock types and qualities present are identified and stored in paper bags, weighed and the mass recorded on the P.N. sheet (Figure 2). A P.N. is calculated for each fraction. The reported P.N. for the sample is calculated by multiplying the P.N. of each individual fraction by the mass per cent of material retained on that sieve. Any sizes not examined are assumed to have the same P.N. of the nearest sieve size

Ministry of Transportation and Communications — Ontario

COARSE AGGREGATE PETROGRAPHIC ANALYSIS

PIT NAME MINISTRY OF TRANSPORTATION LAB NO. 89-14 236
DATE 89-6-15 FRACTION 19.0 - 13.2 ANALYST D.HANNA

TYPE NO.	TYPE	MASS	%	GRANULAR & 16.0 mm CRUSH. CORRECTION	
1	CARBONATES (hard)	550	55.0		
20	CARBONATES (slightly weathered)	16	1.6		
2	CARBONATES (sandy, hard)				
21	CARBONATES (sandy, medium hard)				
23	CARBONATES CRYSTALLINE (hard)				
3	SANDSTONE (hard)	27	2.7		
22	SANDSTONE (medium hard)				
4	GNEISS - SCHIST (hard)	47	4.7		
5	QUARTZITE (coarse and fine grained)	7	0.7		
6	GREYWACKE - ARKOSE (hard and medium hard)	119	11.9		
7	VOLCANIC (hard and slightly weathered)	30	3.0		
8	GRANITE - DIORITE - GABBRO	17	1.7		
9	TRAP	32	3.2		
	TOTAL GOOD AGGREGATE		84.5		
24	CARBONATES CRYSTALLINE (slightly weathered)			x 2	
40	CARBONATES (soft; slightly shaley)			x 2	
41	CARBONATES (sandy, soft and soft pitted)			x 2	
42	CARBONATES (deeply weathered)	5	0.5		
25	GNEISS (soft) SCHIST (medium hard)	27	2.7	x 2	5.4
26	CHERT - CHERTY CARBONATES			x 2	
27	GRANITE - DIORITE - GABBRO (brittle)			x 2	
28	VOLCANIC (soft)			x 2	
52	ENCRUSTATION			x 2	
29	ARGILLITE			x 2	
	TOTAL FAIR AGGREGATE		3.2		
43	CARBONATES (shaley or clayey)	15	1.5		
44	CARBONATES (ochreous)				
45	CHERT - CHERTY CARBONATES (leached)	30	3.0	x5	15
46	SANDSTONE (soft friable)			x3	
48	VOLCANIC (very soft, porous)			x3	
49	CARBONATES CRYSTALLINE (soft)			x3	
50	GNEISS (friable)			x3	
51	GRANITE - DIORITE - GABBRO (friable)			x3	
53	CEMENTATIONS			x3	
54	CEMENTATIONS (total)			x3	
55	SCHIST (soft)			x3	
56	SILTSTONE			x3	
	TOTAL POOR AGGREGATE				
60	OCHRE				
61	SHALE	15	1.5		
62	CLAY	12	1.2		
63	VOLCANIC OR SCHIST (decomposed)	51	5.1		
	TOTAL DELETERIOUS AGGREGATE		7.8		
	TOTALS	1000	100		20.4

% GOOD	84.5 x1 =	84.5	
% FAIR	3.2 x3 =	9.6	
% POOR	4.5 x6 =	27.0	
% DELETERIOUS	7.8 x10 =	78.0	
HOT MIX, MULCH AND CONCRETE P.N.		199.1	

EST. PERCENT CRUSHED	60
EST. PERCENT FLATS & ELONGATED	7
CORRECTED GRANULAR AND 16.0 mm CRUSHED P.N.	178.7

PR-CC-343 79-11 (Formerly CR-MT-84)

FIGURE 2 — Petrographic examination form used in 1989 showing same aggregate as reported in Figure 1

that was examined. The products are totalled to arrive at the final P.N. of the sample. Samples are stored in plastic containers for a period of about two years.

Training and Reference Materials

A controversial aspect of the petrographic examination done by the Ministry of Transportation is the use of technicians rather than geologists for the identification. In the 1950's it was considered that suitable technicians could be trained in about 3 months [3]. In late 1960's it was thought to take about 6 months to adequately train someone with little or no geological background. Today, a year is considered an appropriate training period.

In 1953, five technicians, supervised by a geologist, examined 2300 samples. In 1958, eight technicians examined about 3800 samples or about two samples a day by each technician. In 1988, eight technicians with a petrographer providing technical assistance and resolving problems of identification and classification, examined about 2000 samples of coarse aggregate and 100 samples of fine aggregate.

To assist in training and to convey information to other users of the procedure, the laboratory manual has an appendix describing the properties of the various rock types. The techniques for identification of rocks are not described, but the distinction between such types as: hard carbonate, slightly shaley carbonate and shaley carbonate are covered in some detail. Properties considered of importance are: strength (high, medium, low or very low), porosity, amount of shale seams or leafs. Figure 3 shows how the amount and location of shale leafs or coatings is used to classify carbonates.

In conjunction with the written description of various petrographic types, standard reference materials are also available. These consist of boxes with clear plastic covers containing 48 different rock types and quality varieties. A large quantity of these reference samples were made in the late 1970's and are distributed on request to technicians and consultants doing petrographic examination following the Ontario procedure.

Petrographic Examination and Alkali-Aggregate Reactivity

A low Petrographic Number has sometimes been mistakenly taken to indicate that an aggregate is not likely to be alkali-reactive. Such is not the case, P.N. is only a measure of physical quality. The results of examination are used in conjunction with other tests to warn of the need for further studies for alkali-reactivity. Unfortunately from 1950 to the 1970's a number of alkali-reactive aggregates were inadvertently used in Ontario highway structures. This was not because of incorrect classification of the harmful minerals and rocks present, but because of a failure to recognize that these materials were

Category	Shale Description	Colour	Strength Description
Good	**Carbonates (medium hard)** ... equidimensional particles with a thin shale coating on one face; no interparticle shale seams ... equidimensional particles with one or two interparticle shale seams	generally becoming darker	high strength; can be scratched ; does not soften on immersion in water
Fair	**Carbonates (slightly shaley)** ... equidimensional particles with a thin coating on two faces ... a thick shale coating on one major face ... elongated particle with a thin shale coating on two faces; no interparticle seams ... equidimensional particles with a thin shale coating on one or two faces; two to three interparticle seams present ... equidimensional particles with four interparticle shale seams ... elongated particles with three interparticle shale seams ... uniform shaley (argillaceous) content throughout		medium strength; can be scratched with ease, and scraped with moderate ease; generally shows white or grey streak when scratched; may soften on immersion in water
Poor	**Carbonates (shaley)** ... heavily interbedded with shale or uniformly shaley (argillaceous) content throughout		typically low strength, scraped with ease, and peeled with some difficulty; generally shows grey, brown, or black streak; greasy to touch; usually softens in water
Deleterious	**Shale** ... totally shale		low to very low strength; can be scraped and peeled with ease; softens or slakes in water

FIGURE 3 — Classification of carbonates from appendix of procedure

alkali-reactive. Examples are: greywacke, argillite, sandstones and quartz wackes, and limestones with small amounts of chalcedony, sands with small amounts of chalcedonic chert and quarried Precambrian tacontie (cherty iron formation).

Re-evaluation of the Petrographic Procedure in 1980's

In 1981, the Ontario government funded a re-evaluation of the existing Petrographic Number procedure by P. Hudec [7,8,9]. Thirty bulk samples of the most common rock types and qualities encountered were supplied by the Ministry of Transportation. Hudec tested these materials in a variety of tests to measure porosity and resistance to freezing and thawing. The British Aggregate Impact test was also conducted on dry and water saturated samples. The results are shown in Table 3. It can be seen that in general, with decrease in quality (higher factor) there was an average increase in water absorption, water adsorption, and 5 cycle freeze-thaw loss in 3% NaCl. With decrease in quality there was also a decrease in bulk dry relative density and impact strength. The results of the British Aggregate Impact test are closely correlated with loss in the Los Angeles Abrasion and Impact test. Within any petrographic factor group, there was a very wide variation in properties showing that physical test results by themselves are not sufficient to predict likely performance. In regression analysis, Hudec found that the P.N. factor given a rock type was correlated with: adsorption, vacuum absorption and specific gravity in decreasing order of significance. These three physical properties could largely define the petrographic factor given each rock type.

Hudec [7] found that the factors used did reflect to a 'large degree' the properties of the aggregates and that the P.N. procedure was useful. Hudec concluded [8] that the use of the factors 1, 3, 6 and 10 was unrealistic and that a more gradational approach should be used [1, 2, 3, 4 and so on]. He proposed that the factor given each rock type should be based on the petrographers experience rather than on the rigid factor system.

The changes proposed by Hudec were not adopted for two reasons. At the conception of the procedure it had been established that changes in categorization of rock types should be based as far as possible on field performance in the conditions found in Ontario and not on performance in laboratory tests. If the need for correlation with field performance was abandoned, the procedure would loose its value since some performance characteristics cannnot always be measured in laboratory tests. Secondly, the use of a complex factor system had been used from 1953 to 1960 but abandoned because the use of such factors implied a confidence in correlation with field performance that did not exist. Giving a variable factor to a particular rock type, depending on the nature of the sample and the experience of the technician, had been tried in 1954, but quickly abandoned due to its subjective nature.

TABLE 3 — Summary of Physical Properties of Various Petrographic Types from Hudec [7] and Franklin [10].

Rock Type and quality Classification	P.N. FACTOR	ADSORPTION, 95% Humidity, %	ABSORPTION, 24 hr. Sat., %	ABSORPTION, Vac. Sat., %	RELATIVE DENSITY	POINT LOAD STRENGTH I_{s50} (MPa)	FREEZE-THAW LOSS, %	DRY IMPACT LOSS, %	WET IMPACT LOSS, %
GOOD AGGREGATE									
Gneiss/Schist (Hard)	1	0.058	0.12	0.27	2.717	9.0	0.1	25	27
Carbonate (Med.Hard)	1	0.957	0.20	1.84	2.690	-	8.9	19	22
Crystalline Carbonate	1	0.175	0.04	0.37	2.787	-	1.9	22	26
Volcanic (Hard)	1	0.283	0.30	0.48	2.810	11.4	1.0	8	10
Sandstone (Hard)	1	0.262	0.82	1.29	2.636	4.29	5.1	16	29
Sandstone (Med.Hard)	1	0.280	1.52	1.96	2.582	2.46	6.3	29	32
Granite-Diorite-Gabbro	1	0.190	0.12	0.48	2.752	7.81	2.2	24	27
Sandy Carbonate (Med.Hard)	1	0.980	2.12	2.32	2.605	3.33	4.7	21	17
Carbonate (Med.Hard)	1	0.500	1.33	1.73	2.732	3.36	3.7	17	22
Quartzite	1	0.202	0.16	0.22	2.667	4.58	2.2	19	21
Sandy Carbonate (Hard)	1	0.750	0.48	0.96	2.631	2.79	2.4	21	25
Greywacke-Arkose	1	0.190	0.09	0.19	2.734	8.3	0.4	8	12
Trap (Basalt)	1	0.450	0.05	0.06	3.083	12.4	1.5	9	9
Carbonate (Hard)	1	0.375	0.55	1.20	2.717	4.53	3.4	19	21
AVERAGE		0.404	0.636	0.955	2.725	6.19	3.13	18.3	21.0
FAIR AGGREGATE									
Crystalline Carbonate	3	0.827	1.24	1.69	-	1.00	6.6	25	24
Granite (Brittle)	3	0.325	0.75	0.72	2.636	0.39	5.4	35	36
Carbonate (Slightly Shaley)	3	0.487	1.95	2.12	2.666	2.32	11.6	25	27
Carbonates (Deeply Weathered)	3	0.772	2.74	3.30	2.620	2.51	9.7	25	32
Sandy Carbonates (Soft)	3	0.662	3.00	3.42	2.525	2.49	7.1	25	28
Cherty Carbonate	3	0.390	1.62	1.76	2.622	6.02	3.2	17	17
Gneiss (Brittle)	3	0.160	0.49	0.27	2.730	4.01	4.2	36	36
Carbonates (Encrusted)	3	0.517	-	0.62	2.675	-	4.9	17	20
AVERAGE		0.518	1.684	1.738	2.639	2.68	6.59	25.6	27.5
POOR AGGREGATE									
Carbonates (shaley)	6	1.087	3.15	4.20	2.586	2.13	12.0	30	33
Siltstone (Friable)	6	0.277	2.48	2.35	2.579	6.75	3.3	19	27
Sandstone (Friable)	6	0.572	3.19	4.32	2.483	0.54	10.4	46	41
Chert (leached)	6	0.220	4.23	5.08	2.467	4.55	8.2	14	13
Gneiss (Friable)	6	0.477	1.57	2.24	2.677	0.10	18.5	50	53
AVERAGE		0.527	2.924	3.638	2.558	2.81	10.48	31.8	33.4
DELETERIOUS AGGREGATE									
Shale	10	1.062	2.41	3.36	2.521	5.15	33.4	30	38
Clay	10	1.197	3.42	4.65	2.488	0.14	16.7	52	36
AVERAGE		1.130	2.915	4.005	2.505	2.65	25.05	41.0	37.0

Correlation of Petrographic Number with other tests

Figures 5 to 8 show the relationship of P.N. with some other common measures of aggregate suitability. These figures also show the actual field performance of the individual aggregates. These data were obtained by testing about 100 Ontario aggregates of known performance. Field performance was rated as good (used for many years with no reported failures, popouts, or other signs of poor durability), fair (used at least once where popouts or some reduced service life had occurred, but the pavement or structure gave adequate performance for over ten years), and poor (used once and disintegration occurred, usually after one winter, which severely restricted the serviceable life of the pavement or structure); alternatively the aggregate was of such poor quality that, had it been used, serviceable life could have reasonably been expected to have been reduced. Aggregates that were known to be unsatisfactory because of alkali-aggregate reactivity were not used in the study. The criterion for classification of the field performance was based on the aggregate having adequate strength and resistance to freezing and thawing.

It can be seen in Figures 5 and 6 that there is considerable overlap between 'good', 'fair' and 'poor' performance fields for water absorption and soundness loss against P.N. A considerably better prediction of aggregate performance is found by using P.N. in conjunction with freeze-thaw loss (Figure 7). The freeze-thaw test is a new test on unconfined aggregate, saturated in a 3% sodium chloride solution [11]. Figure 8 shows that there is no correlation between P.N. and Los Angeles Abrasion and Impact loss and also that this latter test was not successful at predicting field performance of concrete aggregates. In Figures 5-8 it can be seen that aggregates with high P.N.'s (>160) invariably have poor or fair field performance. Aggregates with P.N.'s less than 140 almost always have good performance. The exceptions are due to incorrect recognition of certain rock types but these are identified by the freeze-thaw test. Aggregates with intermediate P.N.'s between 140 and 160 fall in a marginal area where performance can vary from good to poor.

Petrographic Number is not adequate by itself for consistently predicting likely field performance, but when combined with an unconfined freeze-thaw test, a very reliable prediction system is available.

Precision of Petrographic Number

The Ministry of Transportation has five regional laboratories where petrographic examination is conducted. Interlaboratory correlation programs are conducted on an annual basis. A scatter diagram for results of a multi-laboratory study of cherty carbonate gravels is shown in figure 4. In this study, all results but those for technician 6 were considered to be due to random variation. Technician 6 was determined to have a bias compared to the population. He did not agree

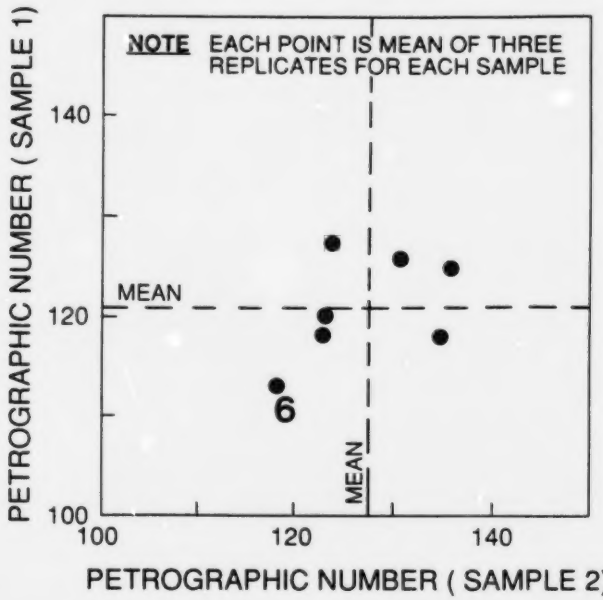

FIGURE 4 — Scatter diagram showing variation obtained by seven different observers on replicate samples of cherty carbonate gravel

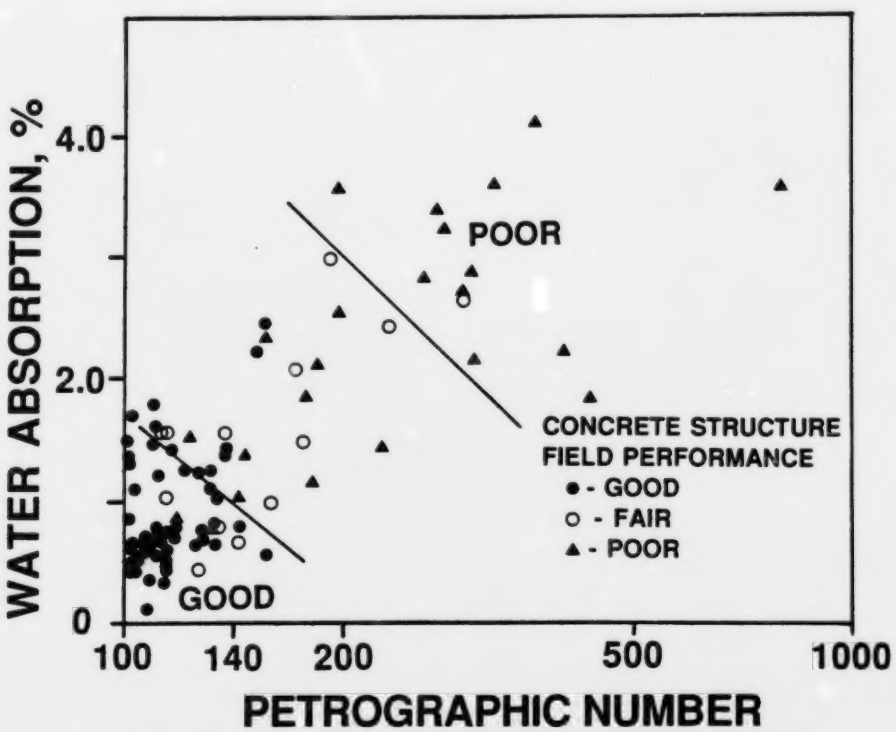

FIGURE 5 — Water absorption against P.N. for samples of coarse aggregate of known performance

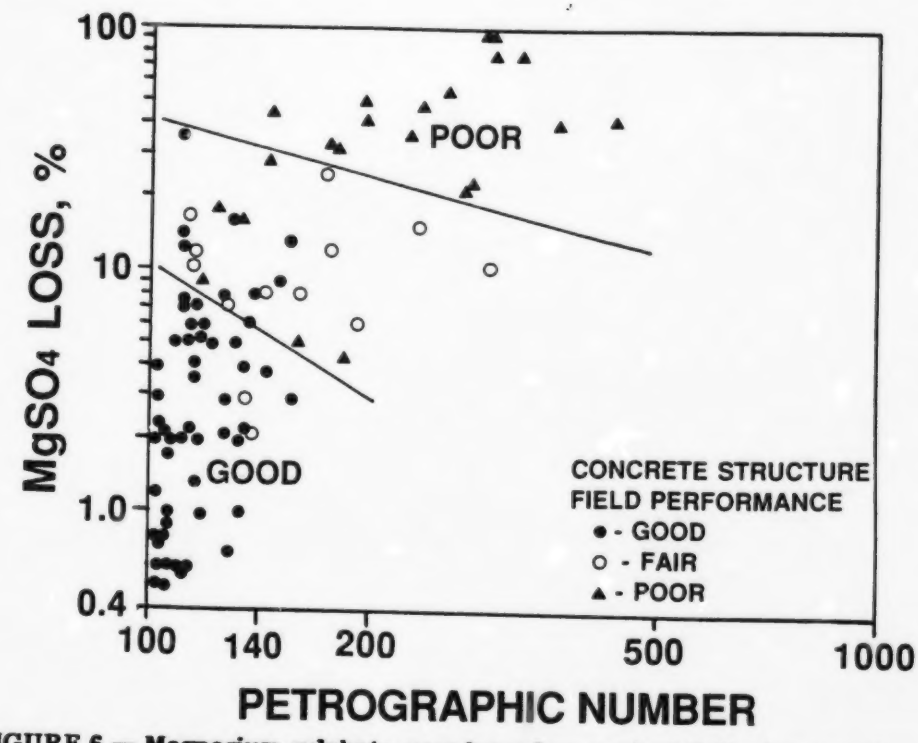

FIGURE 6 — Magnesium sulphate soundness loss against P.N. for samples of coarse aggregate of known performance

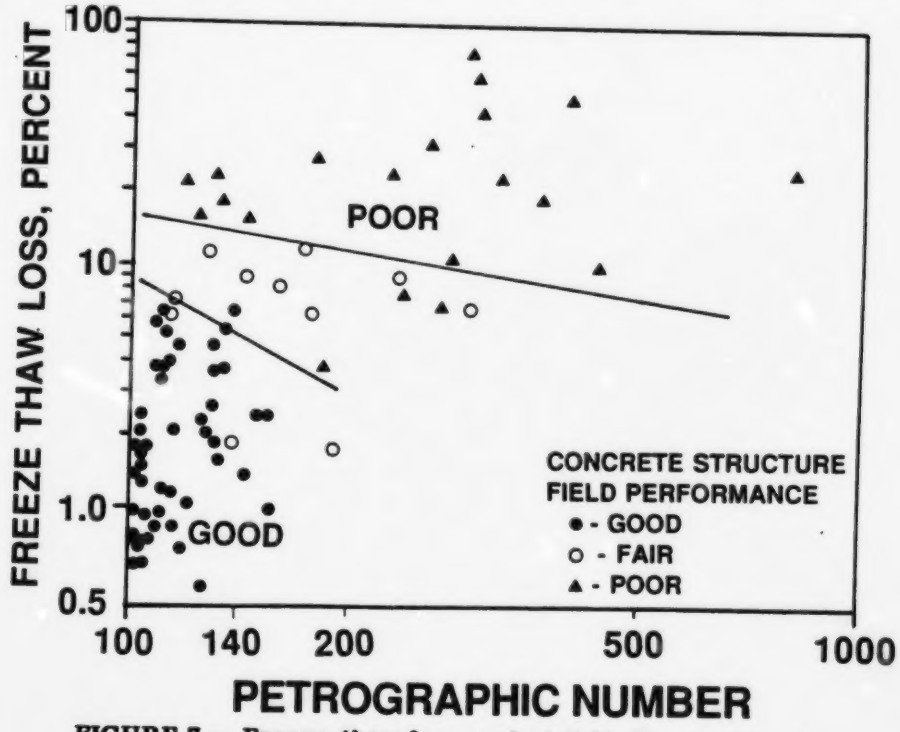

FIGURE 7 — Freeze–thaw loss against P.N. for samples of coarse aggregate of known performance

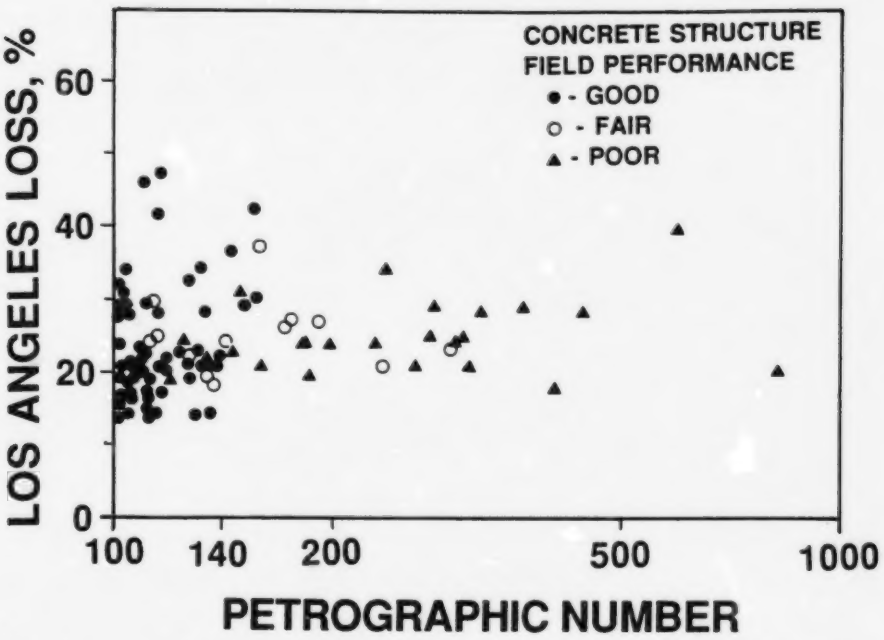

FIGURE 8 — Los Angeles abrasion and impact loss against P.N. for samples of coarse aggregate of known performance

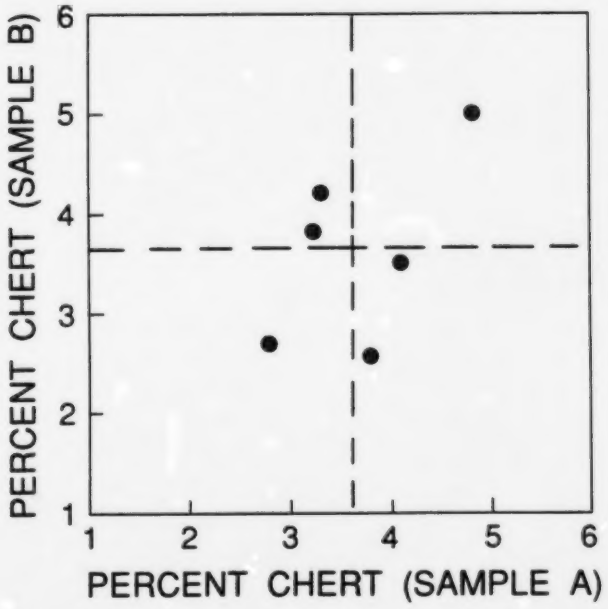

FIGURE 9 — Scatter diagram showing variation in percent chert recorded by six operators on replicate samples of fine aggregate

with others about the classification of slightly cherty carbonate, and was re-trained.

In general, it has been found that the variation in petrographic number of a stockpile of aggregate can vary by up to ±20 on either side of the mean (19 times in 20). This is a maximum and the variation encountered is usually less than ±10. From statistical considerations it has been found that much of this variation is due to chance variation caused by the limited number of particles that are classified in a sample. Improper classification does occur, but in general, is not a significant source of variation if technicians are properly trained. However, in cases of dispute it is appropriate to test about 10 samples to obtain a stable average P.N. for a stockpile.

In other studies, technicians have been asked to classify a large number of different rock types. It has been found that in about 85 per cent of the cases there is agreement between technicians. A seminar is held periodically with all technicians to improve classification techniques and resolve problems of classification of unusual rock types.

Examination of Fine Aggregate

Shortly after the development of the Petrographic Number for coarse aggregate, attempts were made to apply the same principles to fine aggregates. These attempts failed, not because of the difficulty of recognizing poor quality rock types but due to the failure to correlate the results with field performance. Cases of the failure of pavements or structures in Ontario, due to lack of physical suitability of the fine aggregate particles, are extremely rare. Fine aggregates with alkali-reactive chert have caused failure due to alkali reactions, aggregates with excessive amounts of mica or clay have caused failure of granular bases, and aggregates of improper gradation or particle shape have caused difficulty with Portland cement concrete and asphaltic concrete mixture design and properties. But no cases have been observed and studied where breakdown of fine aggregate has caused failure.

In 1952, Bob Bayne [12] experimented with the use of heavy media separation to conduct petrographic examination. He used a mixture of acetylene tetrabromide (tetra bromoethane) and ethylene dibromide to give a solution density of 2.540 at 70°F. A 30g sample of washed sand with the less than 150 um material removed was shaken over the heavy media solution and allowed to settle for 15 minutes. The sink and float portions were then washed with carbon tetrachloride and oven dried. An insoluble residue analysis was then conducted on the sink fraction and the float portion (shale, chert, mica and impure limestone) examined microscopically. The acid insoluble residue was then subjected to a second heavy media separation. The first float fraction was given a factor 6, the second float fraction was given a

factor of 4. All other material was given a factor of 1. A sand Petrographic Nulmber was calculated in the same manner as for the coarse aggregate. This procedure was time consuming, expensive, used toxic chemicals and the results could not be correlated with field performance.

In 1958, George Woda developed another procedure based on the use of a copper nitrate staining test [51gCu$(NO_3)_2$ + 200ml H_2O]. Individual sieve fractions of 200 particles were stained overnight in the solution, washed in distilled water and to intensify the stain, a few drops of ammonium hydroxide solution were added to the final washwater for 3 minutes. The purpose of the stain was to separate limestones from dolostones but also to separate good quality limestones from those of poorer quality. Woda had observed that shaley and highly weathered limestones did not readily accept the stain. The time of soaking was not as long as that used by Dolar-Mantuani [13]. The purpose was to stain but not to cause disintegration of the weaker varieties which may occur when stronger solutions and longer times are used. Following staining, the particles were dried and placed in a line (a shallow groove on a piece of wood was useful) and examined microscopically. The composition of each particle was determined and assigned to one of 33 possible rock or mineral types each with its own petrographic factor. The factors used were very similar to those used for coarse aggregate. A sand P.N. for each sieve size was calculated in the same way as for coarse aggregate, except the per centage of each type was determined by particle count, and not by weighing. A final P.N. was calculated taking into account the original gradation of the sample. This procedure was followed from 1958 until the early 1970's. Very poor correlations were found between sand P.N. and water absorption or sulphate soundness loss. No specifications or guidelines were developed.

In 1983, a new procedure for petrographic examination of fine aggregate was developed. Particles from individual sieve sizes were cemented to 50 x 75 mm glass slides with 5 minute epoxy. The sample could then be lightly etched in a weak acid solution, if desired, and examined at up to 125 x magnification using reflected light. A Swift automatic point counter was used, which moved the sample a predetermined distance after each particle was identified. Up to twelve rock or mineral types could be counted. In normal practice, the silicate rocks and minerals were counted separately from the carbonate rocks and minerals but no further separation was made. The minerals or rocks of most interest were shale or clay, mica or mica schist, chert and jasper, and contamination, such as glass, slag or coal which were counted separately from the carbonates and silicates. 200 particles were counted on each sieve fraction from the pass 4.75 mm to 75 um sieve. The advantage of cementing the particles to the glass is that particles are held strongly enough to be able to scratch them with a needle point and that a permanent mount is made that can be conveniently stored. In cases of difficulty in identification, individual particles could be easily removed for detailed examination using immersion oils under a petrographic microscope or X-ray diffraction.

No specifications have been developed. The results are used to warn of the need for further study such as alkali-reactivity testing or permeability tests on mica bearing granular base materials.

Studies have been done of the variability of the 1983 procedure. Figure 9 shows a scatter diagram of variability in results of the amount of chert in two samples by six observers. The variation found in our studies has been due to operator judgement and random variation. It is necessary to conduct periodic training seminars to reduce variation due to operator judgement. It is also important to realize that it is difficult to precisely measure the amount of deleterious or objectionable material in a sample when it is only present in small quantities. About half of the variation shown in Figure 9 is estimated to be due to variation caused by the limited number of particles (1000) examined.

PETROGRAPHIC EXAMINATION OF CONCRETE

The first Ontario Department of Highways report on petrographic examination of hardened concrete was made by G. Woda in 1959. Popouts occurred under vinyl tiles glued to a two year old concrete floor made with sand dredged from the mouth of the Niagara River. The sand contained trace amounts of broken glass. Particles at the tile/concrete interface had converted to alkali-silica gel and caused bumps in the overlying vinyl tile. The alkali content of the cement was between 0.65 and 0.70% Na_2O equivalent. The source of the glass was broken bottles presumably originating from Niagara Falls.

Since then, many hundreds of examinations have been made of hardened concete. The writing of the reports has been found to sometimes be as time consuming as the examination. A laboratory reporting form has been developed based on the ASTM-C 856 procedure (Figures 10 and 11). This form is easily filled in, being a multiple question type. It has been found that in 90 per cent of the examinations, this form together with a one page letter and photographs is sufficient to adequately report the observations and conclusions. There is a considerable savings in time when using this procedure.

Efflorescent Minerals

Table 4 shows the efflorescent minerals found on concrete surfaces in eastern Canada. In all cases, these sodium and potassium minerals are removed by direct precipitation so they are only normally found in protected areas. Natron ($Na_2CO_3.10H_2O$) has never been conclusively shown to be present. It is an extremely unstable mineral and only forms in very moist areas of low (probably less the 20°C) temperature such as galleries of large dams. It quickly decomposes to thermonatrite and trona on removal for testing. Trona is the most common efflorescent mineral found in Ontario and is commonly found on concrete that is rather porous and also exposed to sodium chloride used

Ministry of Transportation
Ontario

PETROGRAPHIC EXAMINATION OF HARDENED CONCRETE

SAMPLE NO.:

LOCATION

Highway — Crossing Over/Under

County Site # — District — Region

DETAILS OF STRUCTURE

Year of Construction — Contract #

Description of Structure

Description of Deterioration/Problem

CONCRETE DESCRIPTION

(1) Total Concrete:

Hit with Hammer - Ring ☐ Dull ☐
Break with Fingers - Powdery ☐ Friable ☐ Particles Not Dislodged ☐
Strength - Very Strong ☐ Strong ☐ Weak ☐ Very Weak ☐
During Sawing - Clean Cut ☐ Tears Easily ☐
Unsually Wet or Dry Areas - Yes ☐ No ☐
Cement/Coarse Aggregate Bond - Good ☐ Bad ☐
Cement/Fine Aggregate Bond - Good ☐ Bad ☐
Other -

(2) Coarse Aggregate:

Source -
% of Total - %
Material Type - Gravel ☐ Quarried ☐ Mixture ☐
Shape - Rounded ☐ Partly Crushed ☐ 100% Crushed ☐
Distribution - Even ☐ Uneven ☐
Grading - Even ☐ Uneven ☐
Maximum Size (mm) - 10 ☐ 15 ☐ 20 ☐ 25 ☐ ___ ☐
Preferred Orientation - Present ☐ Not Observed ☐

LITHOLOGICAL TYPES	% OF COARSE AGGR.	REACTION RIMS/GEL/FRACTURES	REMARKS

Other -

(3) Fine Aggregate:

% of Total - %
Material Type - Natural ☐ Manufactured ☐ Mixture ☐
Shape - Rounded ☐ Subanglar ☐ Angular ☐
Distribution - Even ☐ Uneven ☐
Grading - Even ☐ Uneven ☐
Preferred Orientation - Present ☐ Not Observed ☐

FIGURE 10 — Page 1 of form used for recording observations in the laboratory during petrographic examination of concrete following ASTM C 856

LITHOLOGICAL TYPES	% OF FINE AGGR.	REACTION RIMS/GEL/FRACTURES	REMARKS

Other -

(4) Cement Paste:

% of Total - %
Appearance in Broken Concrete - Substranslucent ☐ Dull ☐ Chalky ☐
Colour - Grey ☐ Light Grey ☐ White ☐ Blue Green ☐
Colour Distribution - Even ☐ Mottled ☐ Gradational ☐
Strength - Strong ☐ Friable ☐ Powdery ☐
Bleeding - Observed ☐ Not Observed ☐
Carbonation - Outer Skin Only ☐ Along Fractures ☐ Partial ☐ Total ☐
Slag Cement (Greenish Blue, Greenish) - Observed ☐ Not Observed ☐
Evidence of Retempering - Yes ☐ No ☐
Other -

(5) Voids:

% of Total - %
Grading - Even ☐ Uneven ☐ Very Large ☐ Well Air-Entrained ☐ Poorly Air-Entrained ☐
Interior Lustre - Dull ☐ Shining ☐
Interior Condition - Empty ☐ Lined ☐ Partly Filled ☐ Filled ☐
% Voids with Mineralization - Most ☐ About Half ☐ Few ☐ None ☐
Mineralization - Alkali-Silica Gel ☐ Ettringite ☐ Portlandite ☐ Calcium Carbonate ☐
Other -

(6) Cracks:

Amount - Frequent ☐ Occasional ☐ None ☐
Continuity and Distribution -
Location - Through Aggregate Particles ☐ Around Aggregate Particles ☐
Width (mm) -
Filling Material - Alkali-Silica Gel ☐ Ettringite ☐ Portlandite ☐ Calcium Carbonate ☐
Associated with Embedded Items - Yes ☐ No ☐
Other -

(7) Embedded Items:

Description -

Location -

Condition - Clean ☐ Corroded ☐ Decayed ☐
Size (mm) -
Associated Voids, Cracks, Mineralization, Etc. -

Other -

CONCLUSIONS:

SIGNATURE _____ DATE _____

FIGURE 11 — Page 2 of form used for recording observations in the laboratory during petrographic examination of concrete followig ASTM C 856

Table 4 -- Efflorescent minerals found on exterior surfaces of mortar and concrete

Mineral Name	Formula	Remarks
TRONA	$Na_3H(CO_3)_2.2H_2O$	Commonly found on soffit of bridges where significant ingress of NaCl has occurred.
THERMONATRITE	$Na_2CO_3.H_2O$	Dehydration product of natron, ($Na_2CO_3.10H_2O$) found on inspection gallery wall of dam. Commonly found with trona on bridge soffits.
APHTHITALITE	$NaK_3(SO_4)_2$	Found growing on concrete overdosed with superplastizer two hours after mixing.
THENARDITE	Na_2SO_4	Under exfoliating paint on concrete block wall continually wet on the other side. Also found with aphthitalite on mortar joints of brickwalls.
CALCITE	$CaCO_3$	White 'leaching' deposits from cracks in concrete often associated with alkali-silica reaction.

Table 5 -- Strength of concrete made with carbonate or siliceous aggregates and 15 different cements

Coarse and Fine Aggregate Type	Cement Content kg/m^3, Average	Average W/C Ratio	Average 28 Day Compressive Strength, MPa
PALAEOZOIC CARBONATE	311	0.49	40.5
GRANITE AND GNEISS	308	0.49	34.7
PALAEOZOIC CARBONATE	357	0.44	46.3
GRANITE AND GNEISS	352	0.45	38.5

as a de-icing salt. In one case it was found growing in large amounts on the northern surface of highway sound barriers made of no-fines concrete. The south side received direct applications of sodium chloride solution from splashing. The evidence suggests that the source of the sodium, to form Trona, is often sodium chloride rather than sodium hydroxide from the cement paste.

Colour of Concrete

ASTM-C 856 reports that concrete containing blast furnace slag cement retains a blue-green colour in reflected light. Excessively retarded concrete may also show this blue-green colour. This is sometimes mistaken for the presence of blast furnace slag cement when it was not used or used in only moderate amounts. In one case in 1982, the blue-green colour was found in paste adjacent to coarse aggregate particles. In another case (1964) concrete on a canal lining in Niagara Falls was overdosed 5-6 times with a lignin based water reducing admixture. This retarded the set of the concrete which had a uniform dark green colour (W.A. Berry, personal communication). In a more recent case, bridge deck concrete had failed to set after seven days. The concrete had a uniform dark blue-green colour. It was suspected that the concrete had been made with 100 per cent blast furnace slag cement. In Ontario, up to 25 per cent blast furnace slag (B.F.S.) cement is permitted in Ministry of Transportation concrete. This B.F.S. cement is always added from a separate silo at the mixing plant and is not preblended with normal Portland cement. Examination of thin sections of the concrete showed that only about 25 per cent B.F.S. was present. It is thought that excessive retardation was partly responsible for the dark colour of the cement paste.

Blast Furnace Slag (B.F.S.)

The example given above, shows that utility of being able to determine the B.F.S. content of hardened concrete. Figure 12 shows a calibration curve of the amount of visible B.F.S. glass in 25 um thick thin sections against the mass per cent of B.F.S. substitution for normal cement. The larger (>40 um) particles of B.F.S. glass are clearly distinguishable in hardened concrete, having low relief, being isotopic and having a characteristic shape (often triangular in section). Calibration curves should be derived for different B.F.S. cements depending on their grading. This technique is not very precise, probably having an uncertainty of ±10% about a hypothetical true value. It also does not work with B.F.S. cements that have been very finely ground.

From time to time it has been found to be good practice to examine immersion mounts of the +45 um fraction of normal Portland cement sent for routine chemical and physical analysis. In 1985 it was found that one normal Portland cement sold in Ontario consistently contained about 5 per cent B.F.S. While this cement was suitable for normal use, such a cement should be labelled as a type 10SM (slag modified) following

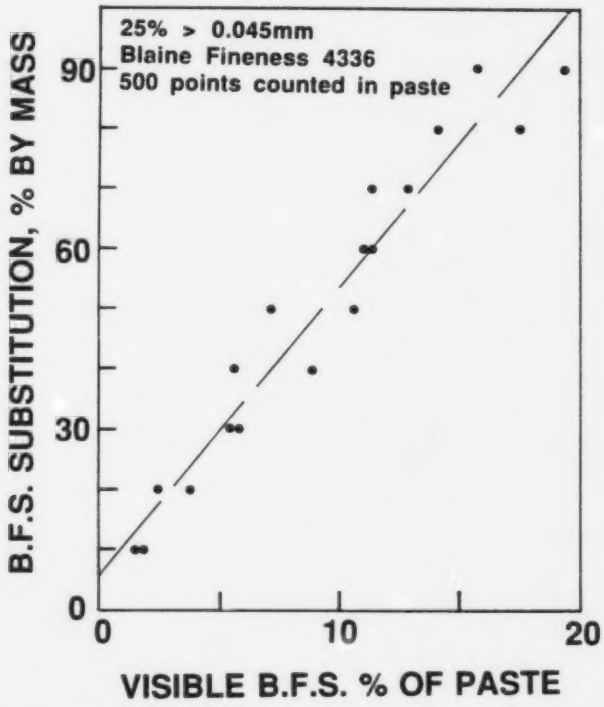

FIGURE 12 — Relationship between substitution of blast furnace slag (B.F.S.) for Portland cement and visible B.F.S. in thin section of concrete

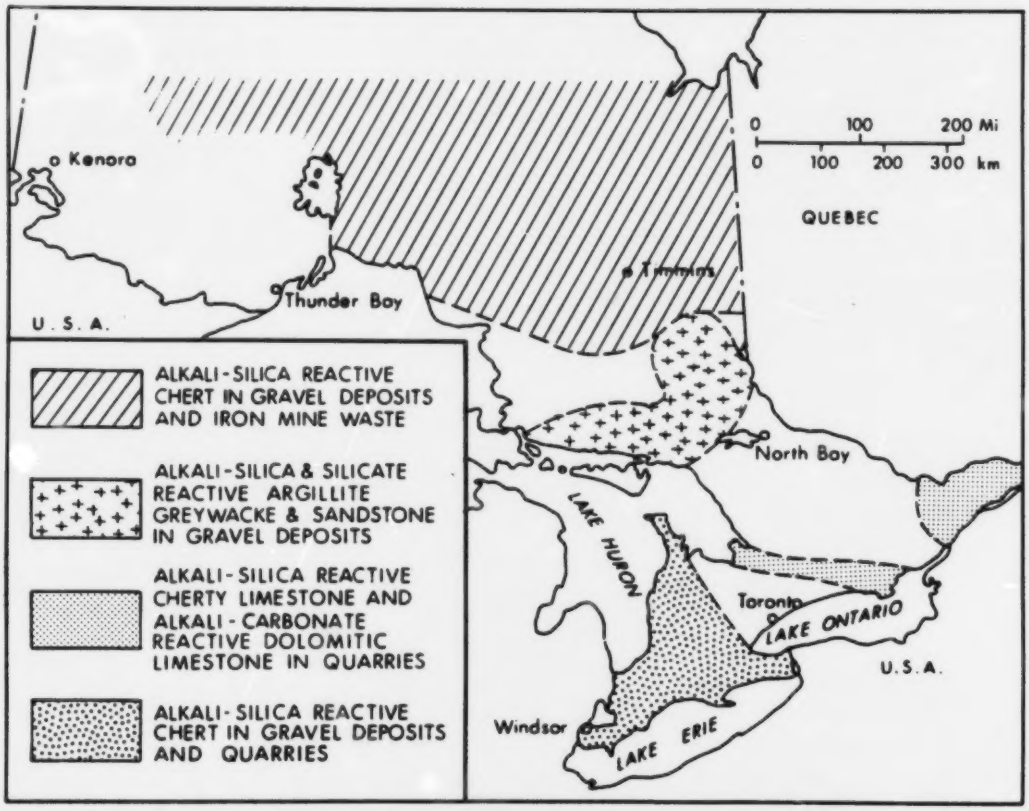

FIGURE 13 — Map showing distribution of potentially alkali-reactive aggregate in Ontario

CSA practice. The cement was being sold as a type 10 without the buyer being aware of the addition of the small amount of B.F.S. The slag is no longer added to this cement as far as can be determined.

Aggregate/Paste Bond

Over half of the surface of Ontario is underlain by Precambrian igneous and metamorphic rocks. In these areas it has generally been found impractical to specify concrete conpressive strengths in excess of 30 MPa at 28 days. In these areas, bridges are designed with this restriction in mind. In areas where carbonate rocks are found, compressive strengths of 35 MPa are assumed in design and are usually easily obtained. The lower practical compressive strength with igneous and metamorphic aggregates is due to a lack of an excellent paste-aggregate bond. Table 5 shows a summary of the results of a compressive strength study of laboratory mixed concrete with a carbonate coarse and fine aggregate from southern Ontario and a siliceous coarse and fine aggregate from the north [15]. It can be seen that, for similar mixtures, the strength of the siliceous aggregate concrete is lower by about 14 and 17 per cent.

In some cases it has been found impossible to design mixtures with siliceous aggregates that meet the 30 MPa requirement and these concretes usually scale excessively in salt scaling tests (ASTM-C 672) with a 3 per cent sodium chloride solution. In these cases, the coarse aggregate has been found to contain over 15 per cent mica, usually of the chlorite variety. In examination of the aggregates, they have usually been judged to have a soapy or slippery feel when handled with moist fingers. In one case, the aggregate was rejected for all uses, in another, a minimum cement content requirement of 355 kg/m^3 was imposed for all applications.

The highest compressive strength recorded for Portland cement concrete in Ontario highway structures is 130 MPa in concrete cores at an age of 20 years. The concrete was precast, made with a type 30 cement with a medium crystalline dolostone coarse aggregate of a maximum size of about 13 mm. In thin section, no unhydrated cement minerals could be distinguished.

Alkali-Reactive Aggregates

A large part of the work of examination of hardened concrete is related to alkali-aggregate reactivity. Engineers frequently wish to know if alkali-aggregate reactions are taking place in deteriorated concrete when making decisions about whether to demolish or to rehabilitate structures. Over two hundred Ontario structures and pavements have been examined in which alkali-aggregate reactivity was considered to be partly responsible for deterioration. A fairly complete knowledge of the types and distribution of alkali-reactive aggregates has been acquired. This is shown in Figure 13. Two unusual

alkali-silica reactive aggregate types merit mention. Precambrian cherty iron formation (taconite) has been found to be alkali-silica reactive in the field and the laboratory. As far as is known it is only deleteriously reactive when it has made up greater than 80 per cent of the coarse aggregate (waste rock from iron mine). In thin section, the chert was a mosaic of anhedral crystals of fine crystalline quartz and magnetite with numerous fluid inclusions. Granite with strained quartz has been found to be alkali-silica reactive in two, 70 year old bridges. The granite was used to give a decorative exposed aggregate finish. In one case the granite contained coarse crystalline strained quartz with an undulatory extinction angle of about 25°. In the other case, the quartz was fine to medium crystalline with an undulatory extinction angle of about 8°. Undulatory extinction angle, by itself, is not a useful measure of the potential alkali-silica reactivity of quartz. The size of the crystals that are measured must also be considered. An undulatory extinction angle of 20° in a crystal of a diameter of 5 mm does not show proportionately the same strain of the crystal as that of 10° measured in a crystal of 1 mm diameter. In Ontario, only granites of the Grenville orogeny show large amounts of undulatory extinction. Older granites have less undulatory extinction, probably because recrystallisation has resulted in removal of any strain originally present.

CONCLUSIONS

Petrographic examination of aggregates, if conducted intelligently, is one of the best ways of assessing the likely suitability of aggregate. In all cases the results of examination must be tempered by a review of actual field performance. Petrographic Number is a useful way of expressing the proportion of good, fair, poor and deleterious rock types present in a sample. P.N. is not adequate by itself for consistently predicting field performance, but when combined with an unconfined freeze-thaw test, a very reliable prediction system is available.

Petrographic examination of concrete is useful for understanding causes of concrete deterioration and reasons for such phenomena as low strength. This can lead to the prevention of future difficulties and improved durability. It is a most cost effective tool in the service of highway authorities.

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APPENDIX 1

EXAMPLES OF PETROGRAPHIC FORMS USED FROM 1951-1976

ANALYST _____ DATE _____ CONTRACT No. _____

PIT NAME _____ SAMPLE No. _____

Rock Types	DESCRIPTION	Wt. in Gms.	%	Factor	Weighted Value
SEDIMENTS					
Limestone	— Angular — Hard		1.0		
	— Pebble — Sound		1.0		
	— Soft — Slightly Weathered		1.5		
	— Rusted		1.4		
	— Mottled		2.0		
	— Mottled with Limonitic Stain		3.0		
	— Sandy		3.0		
	— Shaley		4.0		
	— Clayey		4.0		
	— Ochre-Producing		4.0		
	— Flat-Breaking		2.0		
Dolomite	— Angular — Hard				
	— Pebble — Sound		1.0		
	— Pitted — Hard		1.0		
	— Pitted — Soft — Porous		1.3		
	— Soft — Slightly Weathered		2.0		
	— Flat-Breaking		1.5		
Shale	— Limey		5.0		
	— Black — Soft		6.0		
	— Black — Carbonaceous		6.0		
Sandrtone	— Hard		1.5		
	— Average — Scratches easily		3.0		
	— Soft — Friable		4.5		
Chert	—		5.0		
Clay	— As a product of L.S. or Dol.		6.0		
	— Clay Ball		6.0		
METAMORPHICS					
	— Greywacke — Arkose, etc.		1.0		
	— Granite Gneiss		1.2		
	— Biotite — Hornblende — Gneiss hard		1.4		
	— Quartzite — Very fine grained		1.6		
	— Quartzite — Coarse grained		1.2		
	— Crystalline Limestone		1.5		
	— Biotite or Hornblende Gneiss soft		4.0		
	— Soft Schists		4.0		
IGNEOUS					
	— Granites — Syenite — Diorite		1.0		
	— Trap — Andesite — Basalt		0.9		
MISCELLANEOUS					
	— Encrustation		2.0		
	— Cementation		3.0		

Rock Types	Quality — Per Cent			
	Excellent	Good	Fair	Poor
	0.9	1.0 – 1.3	1.4 – 3.5	3.5 – 6.0

Remarks _____

FIGURE 1 - Petrographic examination form used in 1951.

FORM OB-ML-85
FEB 59

PETROGRAPHIC ANALYSIS OF SAND

SAMPLE NO. _____ DATE _____

PIT NAME _____

FRACTIONS	WT. IN GRAMS	%	P.N. OF FRACTION	WEIGHTED VALUE TO WHOLE SAMPLE
# 8				
# 14				
# 28				
# 48				
# 100				
< 100				
TOTALS				P.N.

CONSTITUENTS	FACTOR	# 8		# 14		# 28		# 48		# 100		< 100		REMARKS
		%	VALUE	%	VALUE	%	VALUE	%	VALUE	%	VALUE	%	VALUE	
Quartz & Quartzite	1.0													
Granite - Gabbro	1.0													
Carbonates (Ls, Dol.)	1.0													
Greywacke - Arkose	1.0													
Andesite - Basalt	1.0													
Volcanic	1.0													
Hard Gneiss and Granite Gneiss	1.2													
Amphibole & Pyrox.	1.2													
Accessory Minerals	1.2													
Sandstone Hard	1.2													
Arenaceous Carb.	1.4													
Green Schist	1.5													
Soft Carbonates	1.5													
Cryst. Carb. (Marble)	1.5													
Volcanic Soft	1.5													
Carb. Porous Pitted	2.0													
Sandstone Average	2.0													
Volcanic Porous	2.0													
Chert Brownish	2.0													
Encrustation	2.0													
Cryst. Carb. Soft	3.0													
Mineral Dust	3.0													
Cherty Carb.	3.0													
Brittle Granite	3.0													
Shaley, Clayey Carb.	4.0													
Soft Gneiss (Granite)	4.0													
Soft Schist	4.0													
Sandstone Soft	4.5													
Micacious Min.	4.5													
Chert White - Black	5.0													
Calcar. Shale	5.0													
Gneiss Decomp.	5.0													
Shale & Clay	6.0													

ANALYST _____

FIGURE 2 - Form for petrographic analysis of sand, 1959.

FORM DH-ML-84
REVISED MARCH 85

DEPARTMENT OF HIGHWAYS - ONTARIO
MATERIALS AND RESEARCH SECTION

COARSE AGGREGATE PETROGRAPHIC ANALYSIS

PIT NAME _____ LAB. NO _____

DATE _____ FRACTION _____ ANALYST _____

TYPE NO.	TYPE	WEIGHT	%	TYPE NO	CURRENT FACTOR	CURRENT WEIGHTED VALUE	BASIC FACTOR	BASIC WEIGHTED VALUE
1	CARBONATES (hard)			1	1.0		1	
2	SANDSTONE (hard)			2	1.0		1	
3	VOLCANIC (slightly weathered)			3	1.5		1	
4	GRANITE GNEISS			4	1.2		1	
5	QUARTZITE (coarse grained)			5	1.2		1	
6	GREYWACKE - ARKOSE			6	1.0		1	
7	GRANITE - DIORITE			7	1.0		1	
8	TRAP			8	1.0		1	
11	CARBONATES (sandy)			11	2.5		3	
12	CARBONATES (slightly weathered)			12	1.5		3	
13	SANDSTONE (medium hard)			13	3.0		3	
14	CRYSTALLINE LIMESTONE (hard)			14	1.5		3	
15	CRYSTALLINE L.S (slightly weathered)			15	2.0		3	
16	HORNBLENDE BIOTITE GNEISS			16	1.4		3	
21	CARBONATES (soft)			21	2.0		6	
22	CARBONATES (deeply weathered)			22	2.0		6	
23	CARBONATES (shaley or clayey)			23	4.0		6	
24	CARBONATES (ochre producing)			24	4.0		6	
25	SANDSTONE (soft friable)			25	6.0		6	
26	CHERT - CHERTY CARBONATES			26	5.0		6	
27	CARBONATES (soft arenaceous)			27	4.0		6	
28	VOLCANIC (sheared, soft)			28	2.0		6	
29	QUARTZITE (fine grained)			29	1.6		6	
30	CRYSTALLINE LIMESTONE (soft)			30	3.0		6	
31	HORNBLENDE BIOTITE GNEISS (soft)			31	4.0		6	
32	GRANITE (brittle)			32	2.5		6	
33	CEMENTATIONS			33	3.0		6	
34	CEMENTATION (total)			34	6.0		6	
35	ENCRUSTATION			35	2.0		6	
41	CARBONATES (ochre)			41	6.0		10	
42	SHALE			42	6.0		10	
43	CLAY			43	6.0		10	
44	SCHIST (soft)			44	4.0		10	
45	VOLCANIC (decomposed)			45	4.0		10	
46	GNEISS (decomposed)			46	5.0		10	
	TOTALS							

PETROGRAPHIC NO. _____ CURRENT _____ BASIC

FIGURE 3 - Petrographic examination form used in 1959.

FORM 08-MT-84

DEPARTMENT OF TRANSPORTATION AND COMMUNICATIONS
MATERIALS AND TESTING OFFICE

COARSE AGGREGATE PETROGRAPHIC ANALYSIS

PIT NAME _____ LAB. NO. _____

DATE _____ FRACTION _____ ANALYST _____

TYPE NO.	TYPE	WEIGHT	%
1	CARBONATES (hard)		
2	CARBONATES (sandy, hard)		
3	SANDSTONE (hard)		
4	GNEISS (hard)		
5	QUARTZITE (coarse grained)		
6	GREYWACKE – ARKOSE		
7	VOLCANIC (slightly weathered)		
8	GRANITE – DIORITE		
9	TRAP		
20	CARBONATES (slightly weathered)		
21	CARBONATES (sandy, medium hard)		
22	SANDSTONE (medium hard)		
23	CARBONATES CRYSTALLINE (hard)		
24	CARBONATES CRYSTALLINE (slightly weathered)		
25	GNEISS (soft)		
26	CHERT – CHERTY CARBONATES		
27	GRANITE (brittle)		
28	VOLCANIC (soft)		
40	CARBONATES (soft, slightly shaley)		
41	CARBONATES (sandy, soft)		
42	CARBONATES (deeply weathered)		
43	CARBONATES (shaley or clayey)		
44	CARBONATES (ochreous)		
45	CHERT – CHERTY CARBONATES (light leached)		
46	SANDSTONE (soft friable)		
47	QUARTZITE (fine grained)		
48	VOLCANIC (very soft, porous)		
49	CARBONATES CRYSTALLINE (soft)		
50	GNEISS (friable)		
51	GRANITE (friable)		
52	ENCRUSTATION		
53	CEMENTATIONS		
54	CEMENTATIONS (total)		
55	SCHIST (soft)		
60	OCHRE		
61	SHALE		
62	CLAY		
63	VOLCANIC (decomposed)		

ESTIMATED PERCENT CRUSHED		TOTALS	
ESTIMATED PERCENT FLATS AND ELONGATED		BASIC PETROGRAPHIC NO.	

FIGURE 4 - Petrographic examination form used in 1965.

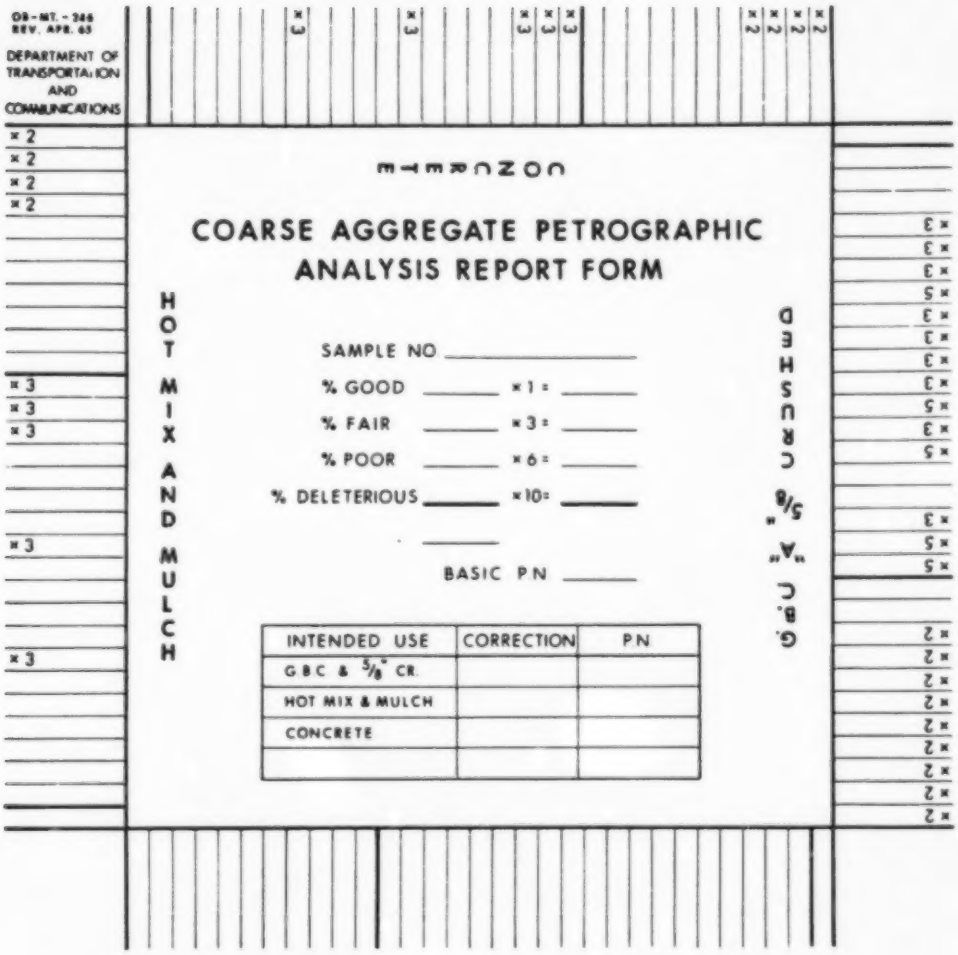

FIGURE 5 - Correction chart used with 1965 form.

Ministry of Transportation and Communications Ontario

COARSE AGGREGATE PETROGRAPHIC ANALYSIS

PIT NAME _____ LAB. NO. _____

DATE _____ FRACTION _____ ANALYST _____

TYPE NO	TYPE	WEIGHT	%	HOT MIX MULCH OR CONCRETE		G.B.C. 'A' 5/8" CRUSHED	
1	CARBONATES (hard)						
2	CARBONATES (sandy, hard)						
3	SANDSTONE (hard)						
4	GNEISS (hard)						
5	QUARTZITE (coarse grained)						
6	GREYWACKE – ARKOSE						
7	VOLCANIC (slightly weathered)						
8	GRANITE – DIORITE						
9	TRAP						
	TOTAL GOOD AGGREGATE						
20	CARBONATES (slightly weathered)			× 2		× 2	
21	CARBONATES (sandy, medium hard)			× 2		× 2	
22	SANDSTONE (medium hard)			× 2		× 2	
23	CARBONATES CRYSTALLINE (hard)			× 2		× 2	
24	CARBONATES CRYSTALLINE (slightly weathered)					× 2	
25	GNEISS (soft)					× 2	
26	CHERT – CHERTY CARBONATES					× 2	
27	GRANITE (brittle)					× 2	
28	VOLCANIC (soft)					× 2	
40	CARBONATES (soft, slightly shaley)			× 3		× 5	
41	CARBONATES (sandy, soft)			× 3		× 5	
42	CARBONATES (deeply weathered)			× 3		× 3	
43	CARBONATES (shaley or clayey)						
44	CARBONATES (ochreous)						
45	CHERT - CHERTY CARBONATES (light leached)					× 5	
46	SANDSTONE (soft friable)					× 3	
47	QUARTZITE (fine grained)			× 3		× 5	
48	VOLCANIC (very soft, porous)					× 3	
49	CARBONATES CRYSTALLINE (soft)					× 3	
50	GNEISS (friable)					× 3	
51	GRANITE (friable)					× 3	
52	ENCRUSTATION			× 3		× 5	
53	CEMENTATIONS					× 3	
54	CEMENTATIONS (total)					× 3	
55	SCHIST (soft)					× 3	
56	SILTSTONE					× 3	
60	OCHRE						
61	SHALE						
62	CLAY						
63	VOLCANIC OR SCHIST (decomposed)						
	TOTAL DELETERIOUS AGGREGATE						
			TOTALS				

% GOOD _____ ×1 = _____

% FAIR _____ ×3 = _____

% POOR _____ ×6 = _____

% DELETERIOUS _____ ×10 = _____

BASIC PETROGRAPHIC NO. [ ]

EST. PERCENT CRUSHED	
EST. PERCENT FLATS AND ELONGATED	

INTENDED USE	CORRECTION	P.N.
G.B.C. & 5/8" CR.		
HOT MIX & MULCH		
CONCRETE		

08-MT-84 1-76

FIGURE 6 - Petrographic examination form used in 1976.